Search for the Higgs boson in the WW decay channel with the ATLAS Detector

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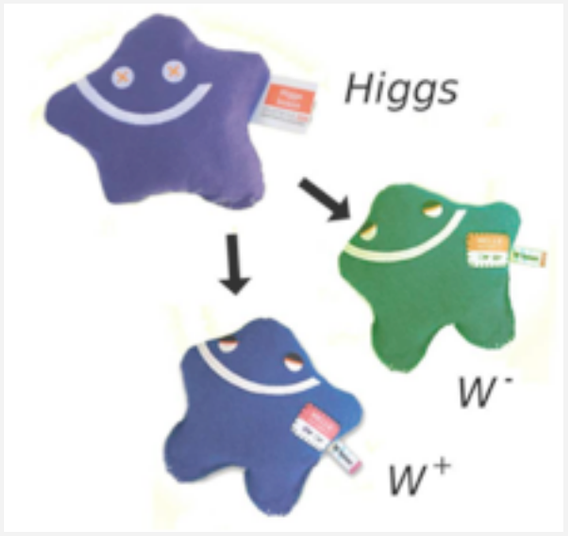
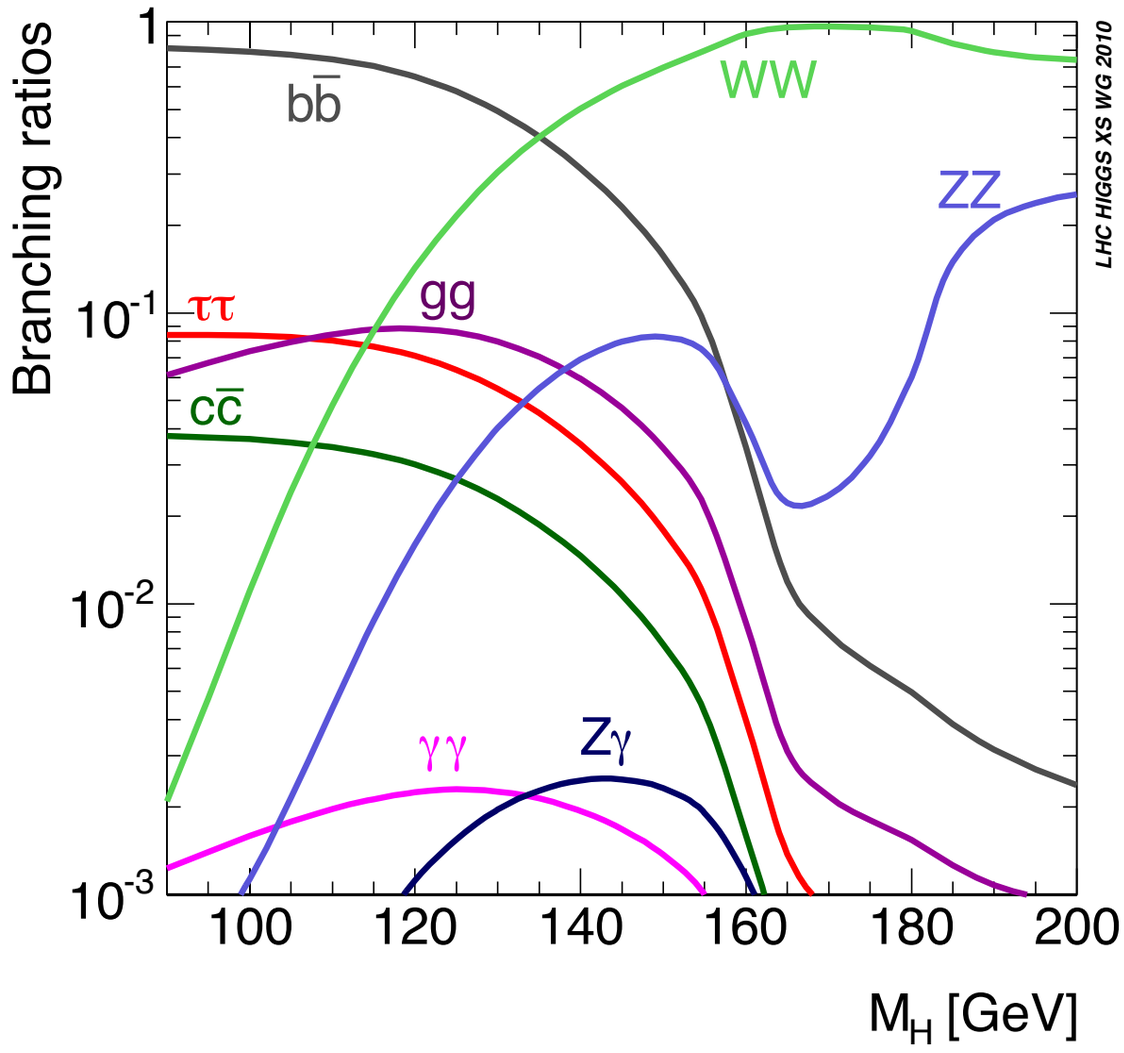


- Introduction
- H→WW(*)→lvlv
- H→WW→lvqq
- Conclusions

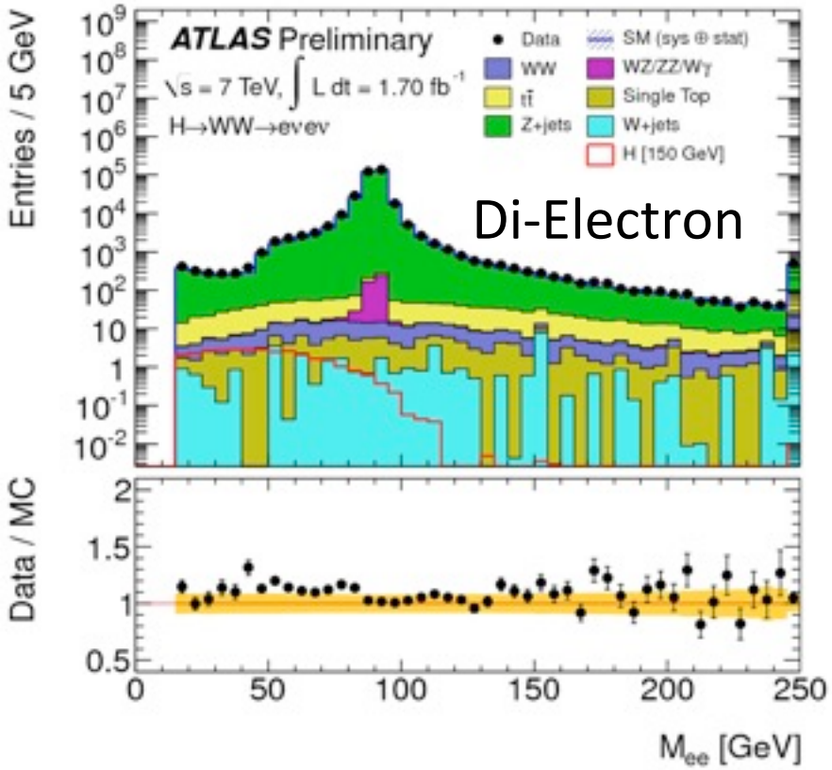
Introduction

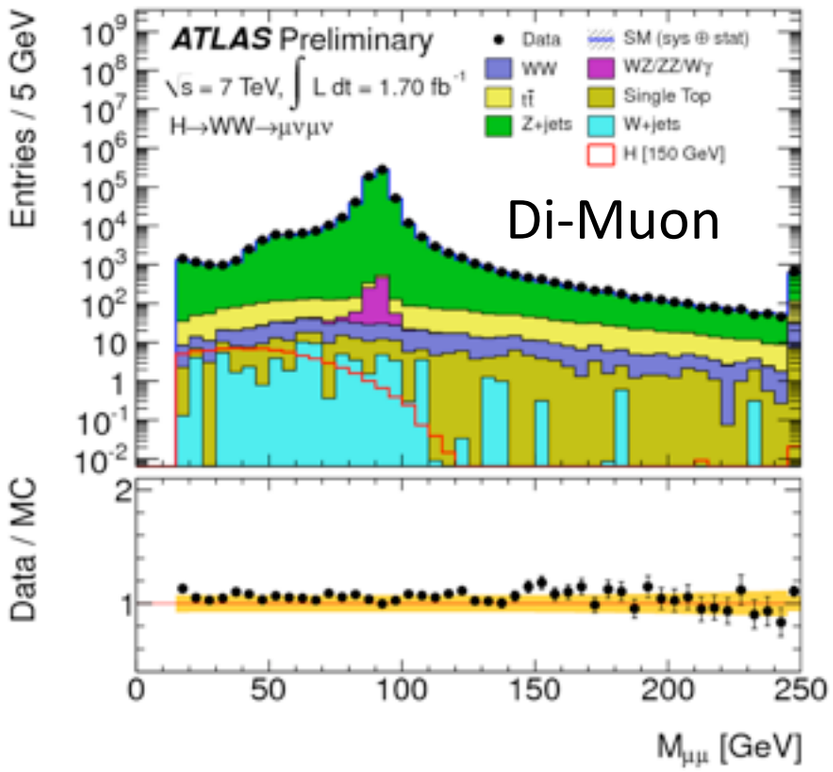
- The 40 year long search for finding or disproving the existence of the Higgs boson is nearing its end
  - ATLAS dataset enough to have sensitivity for a range of masses
- The $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ channel combines the large $H \rightarrow WW$ branching ratio with a clean final state
  - Analysis performed for $110 < M_H < 300$ GeV

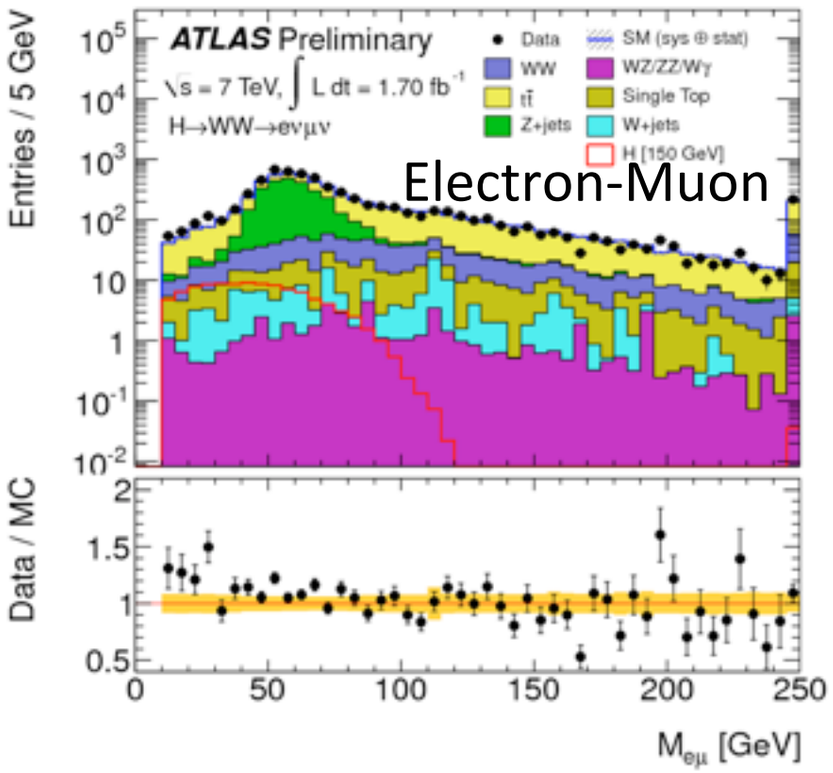


Lepton Selection

- Select events containing exactly two opposite sign leptons (e or μ)
- Cut on di-lepton invariant mass to reduce Z+jet background
  - ee, μμ: $m_{ll} > 15$ GeV, $|m_{ll} - m_Z| > 15$ GeV
  - eμ: $m_{ll} > 10$ GeV







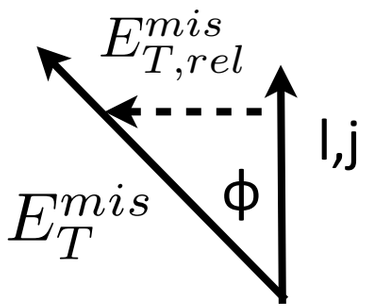
Require large missing energy

- Require missing energy to suppress QCD and Z/γ*+jets backgrounds
- Use

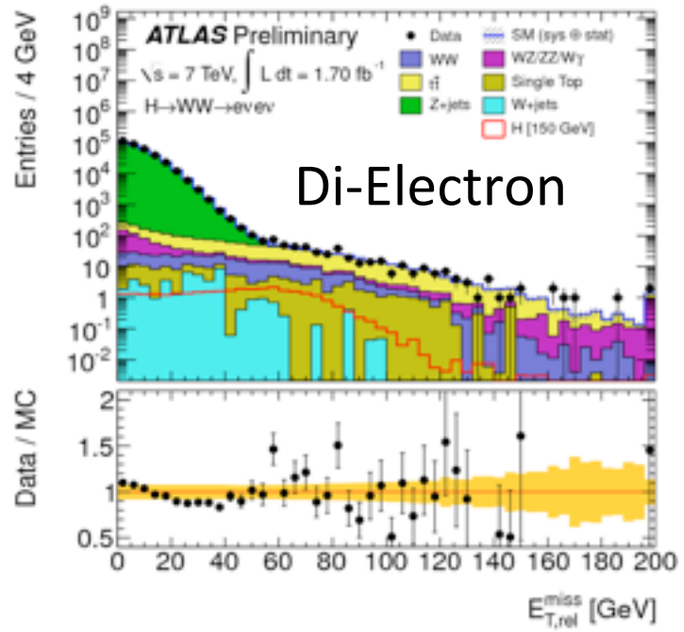
$$E_{\mathrm{T,rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \cdot \sin\Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases}$$

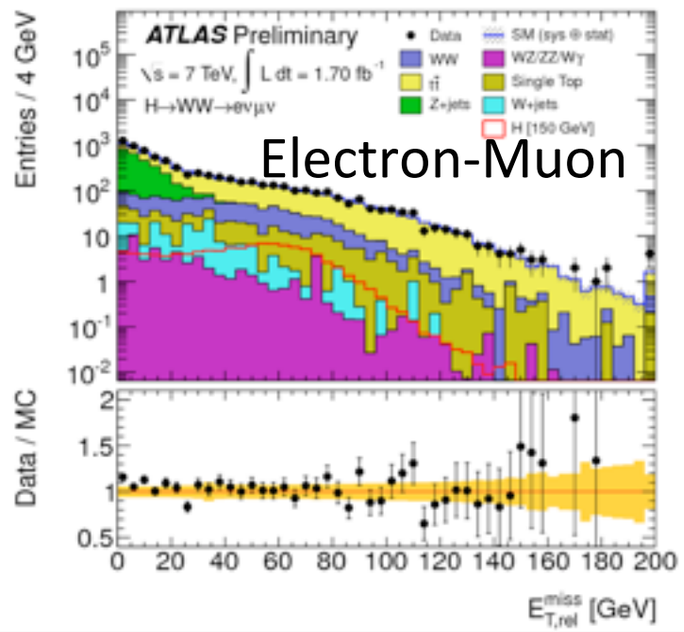
$$\Delta\phi = min(\Delta\phi(E_T^{mis}, l), \Delta\phi(E_T^{mis}, j)$$

- Same flavour: $E_{T,rel}^{mis} > 40$ GeV
- Opposite flavour: $E_{T,rel}^{mis} > 25$ GeV



Suppresses also ‘fake’ MET from mis-measurement



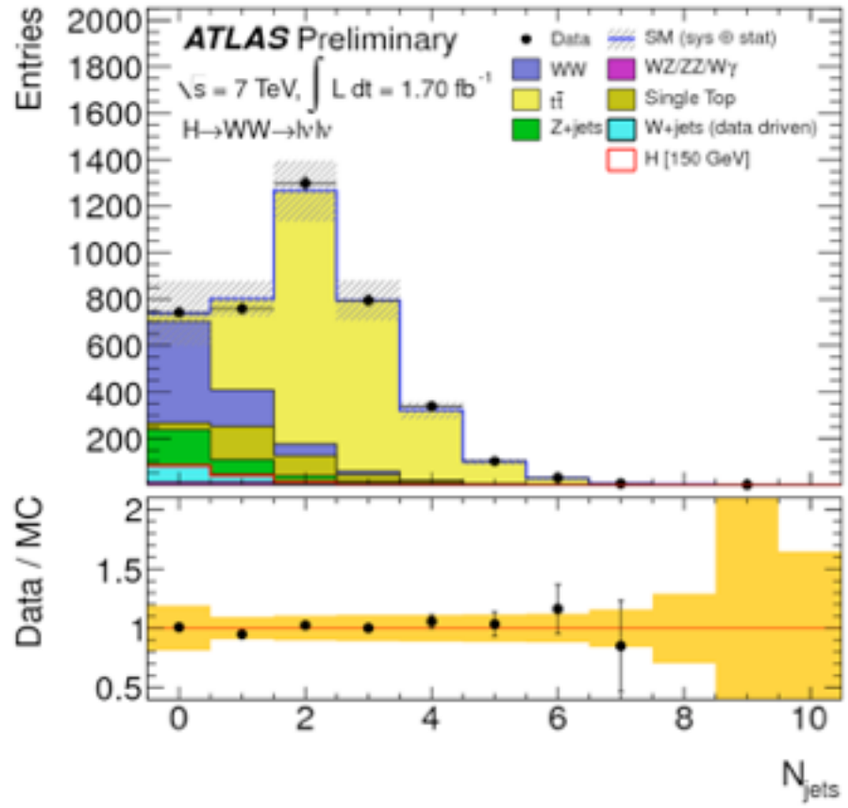


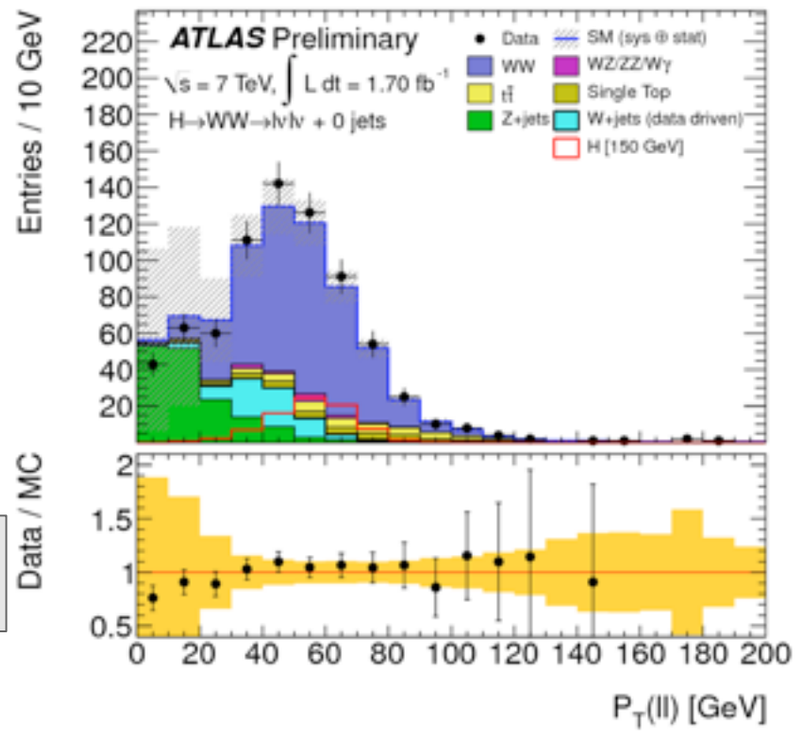
	WW	$Z/\gamma^* + \mathrm{jets}$	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
$m_{\ell\ell} > 15$ GeV, $m_{e\mu} > 10$ GeV	1380 ± 100	970000 ± 70000	6200 ± 600	630 ± 70	1200 ± 100	970000 ± 70000	997813
$\lvert m_Z - m_{\ell\ell}\rvert > 15$ GeV	1220 ± 80	91000 ± 7000	5500 ± 600	560 ± 60	92 ± 9	98000 ± 7000	104253
$E_{\mathrm{T,rel}}^{\mathrm{miss}}$	660 ± 50	300 ± 200	2700 ± 300	310 ± 40	28 ± 4	4000 ± 500	4051

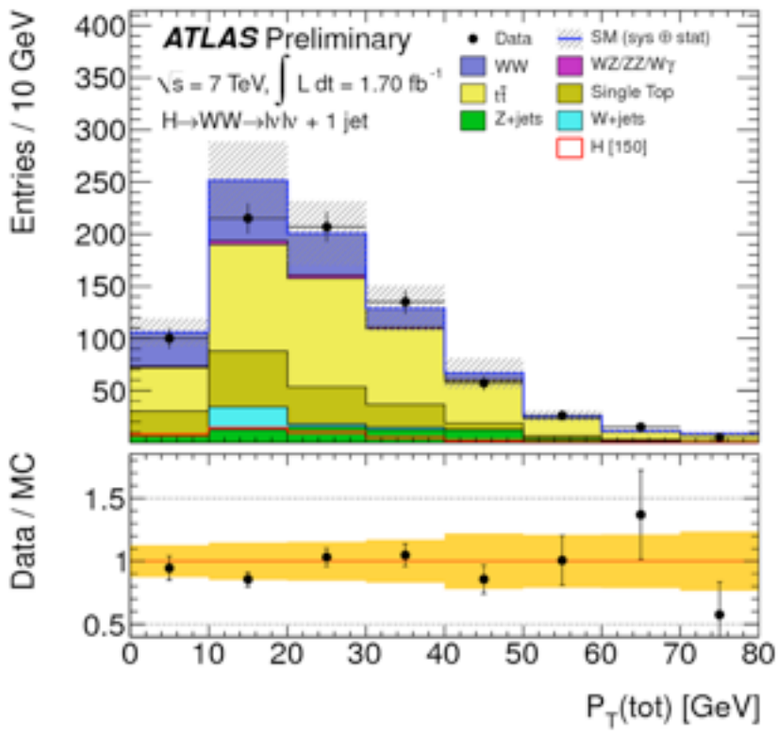
Jet Multiplicity

- Further categorize events by jet multiplicity for jets with $p_T > 25$ GeV, $|\eta| < 4.5$
  - **0j**: Zero jets
  - **1j**: Exactly 1 jet, no b-tag
- Different signal sensitivity and background composition
- Cuts for 0j: Cuts: $p_T^{ll} > 30$ GeV
- Cuts for 1j:
  - no tagged b-jet
  - $p_T^{tot} < 30$ GeV
  - $|m_{\tau\tau} - m_Z| < 25$ GeV

$$p_T^{tot} = p_T^{l1} + p_T^{l2} + p_T^{j} + p_T^{miss}$$



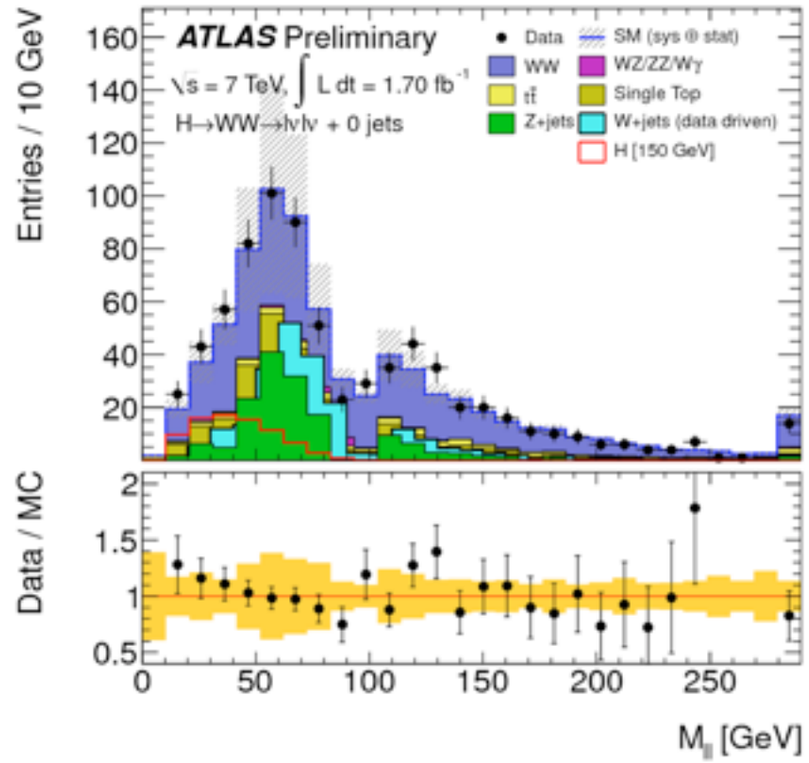


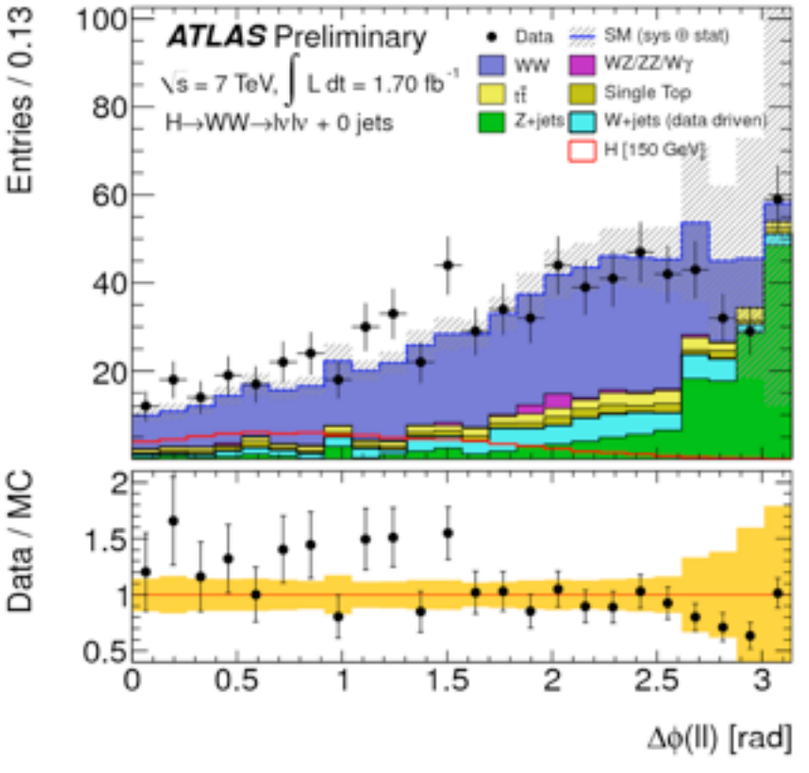


Topological Selection

- Irreducible WW background: topological cuts to exploit Higgs mass and spin
- Values optimized in 3 Higgs mass ranges
- Dilepton Invariant Mass, m_{ll}
  - m_{ll}< 50 GeV (m_H< 170 GeV)
  - m_{ll}< 65 GeV (170 <= m_H< 220 GeV)
  - 50< m_{ll} < 180 GeV (m_H>= 220 GeV)
- Opening angle between leptons, $\Delta\Phi$
  - $\Delta\Phi$ < 1.3 (m_H< 170 GeV)
  - $\Delta\Phi$ < 1.8 (170 <= m_H< 220 GeV)
- Sliding window cut on transverse mass
  - 0.75 m_H< m_T< m_H (m_H< 220 GeV)
  - 0.6 m_H< m_T< m_H (m_H>= 220 GeV)

$$M_T = \sqrt{(E_T^{ll})^2 + (E_T^{\nu\nu})^2 - (\vec{p}_T^{\,ll} + \vec{p}_T^{\,miss})^2}$$





H→WW→lνlν + 0j

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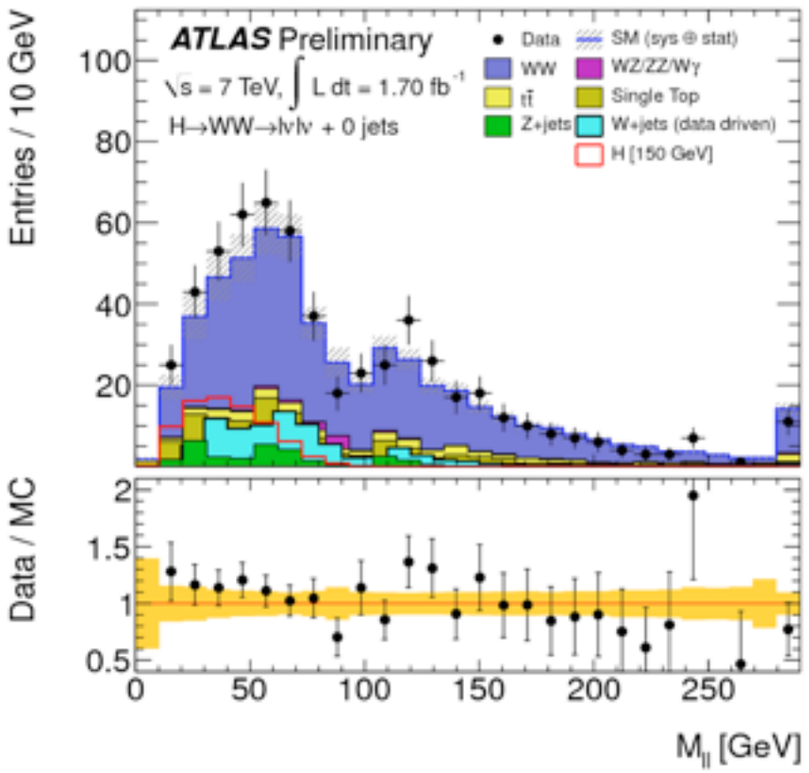
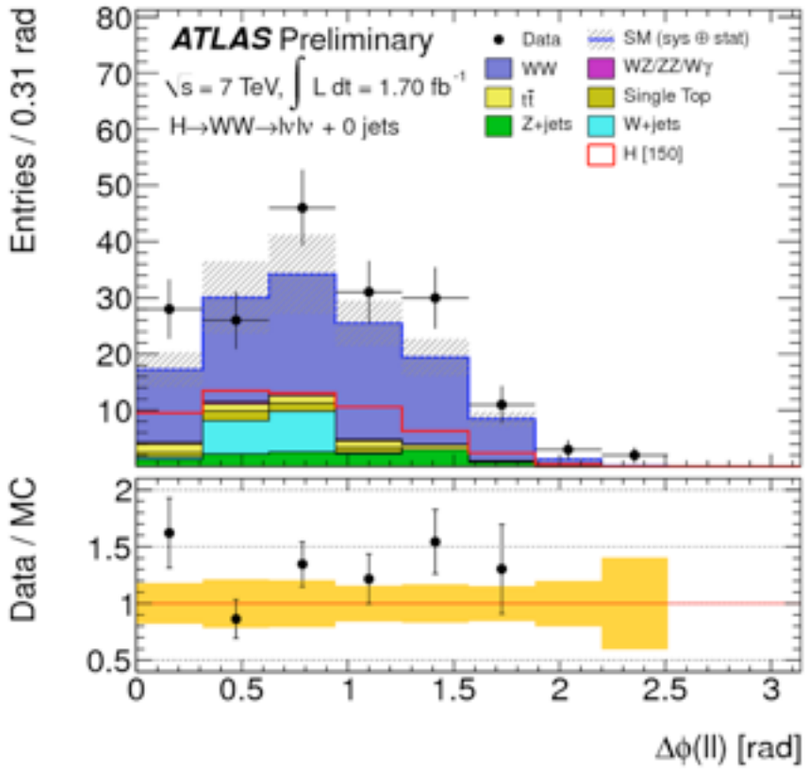
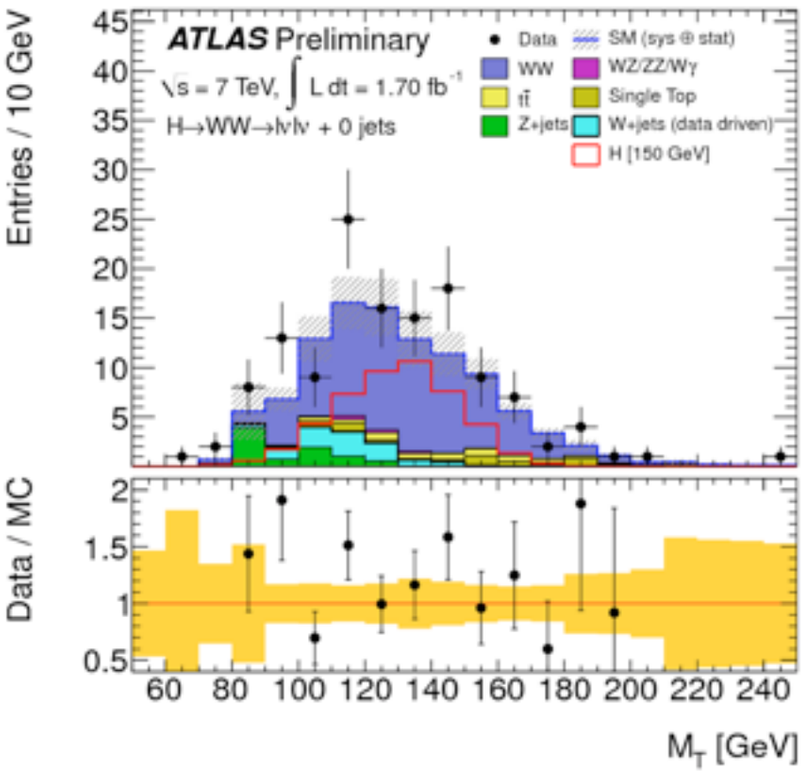
m_H = 150 GeV Selection

	Signal	WW	W + jets	Z/γ^* + jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
Jet Veto	82 ± 17	430 ± 40	70 ± 40	160 ± 150	37 ± 13	28 ± 7	11 ± 3	740 ± 160	738
$\lvert\mathbf{P}_{\mathrm{T}}^{\ell\ell}\rvert > 30$ GeV	79 ± 17	390 ± 40	60 ± 30	28 ± 11	35 ± 12	25 ± 7	10 ± 3	540 ± 80	574
$m_{\ell\ell} < 50$ GeV	56 ± 12	98 ± 13	17 ± 7	12 ± 7	6 ± 3	4.8 ± 1.5	1.2 ± 0.4	139 ± 20	175
$\Delta\phi_{\ell\ell} < 1.3$	48 ± 11	76 ± 10	9 ± 4	8 ± 6	5 ± 2	4.8 ± 1.5	1.1 ± 0.3	105 ± 16	131
$0.75\,m_H < m_{\mathrm{T}} < m_H$	34 ± 7	43 ± 6	5 ± 2	2 ± 4	2.2 ± 1.4	1.2 ± 0.8	0.7 ± 0.3	53 ± 9	70
ee	5.2 ± 1.2	6.2 ± 0.9	0.9 ± 0.4	0.8 ± 1.4	0.3 ± 0.3	0 ± 0.3	0.07 ± 0.05	8.2 ± 1.7	9
$e\mu$	17 ± 4	22 ± 3	2.8 ± 1.3	0 ± 1.3	1.1 ± 0.5	0.8 ± 0.6	0.31 ± 0.19	27 ± 4	32
$\mu\mu$	11 ± 2	14 ± 2	1.0 ± 0.6	1 ± 3	0.8 ± 1.1	0.4 ± 0.4	0.31 ± 0.09	18 ± 5	29

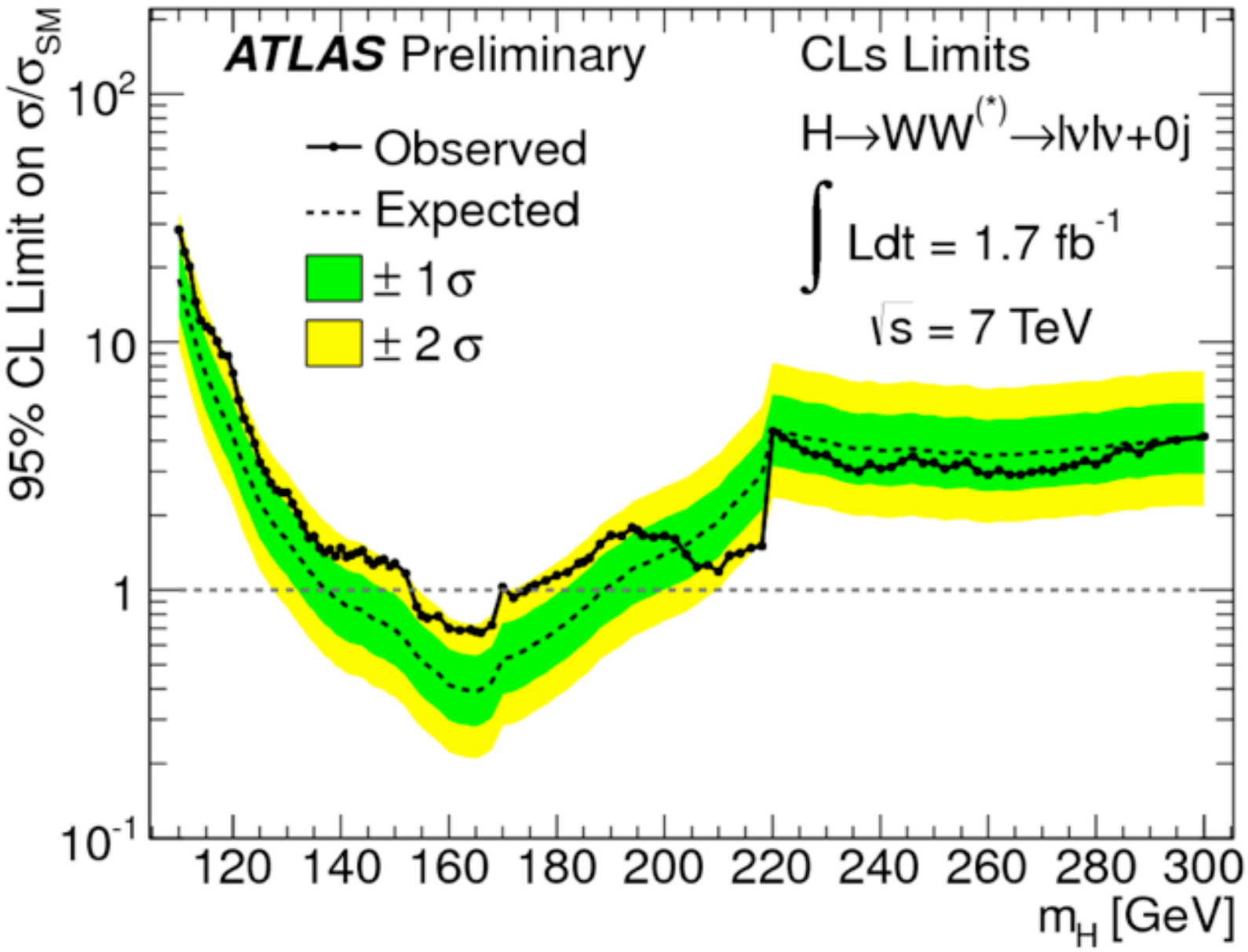






H→WW→lνlν + 0j Limits

- Exclude a range of Higgs masses with the 0j channel alone
- Kink due to cut change at m_H= 220 GeV



H→WW→lνlν + 1j

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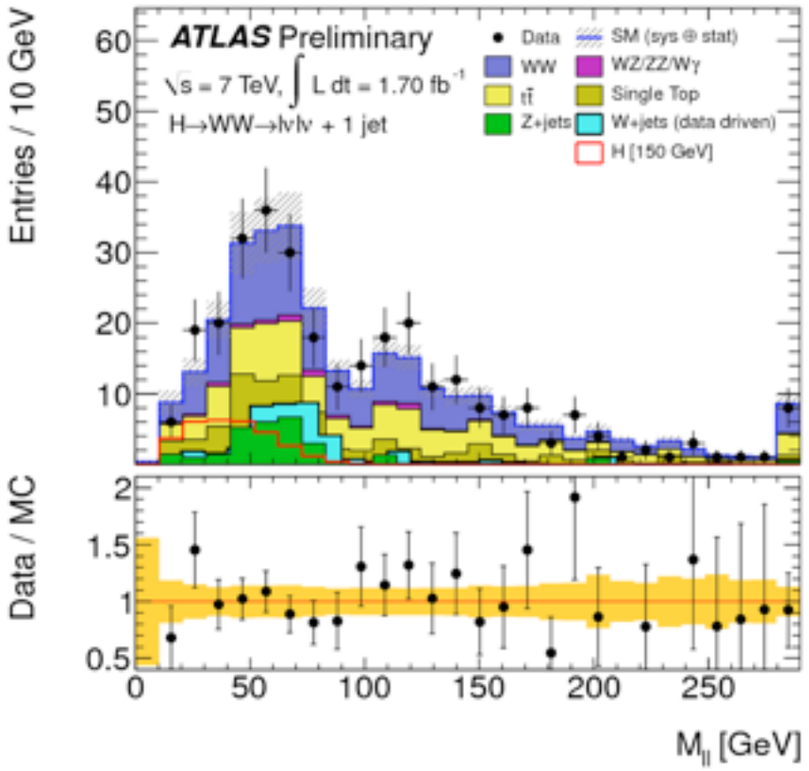
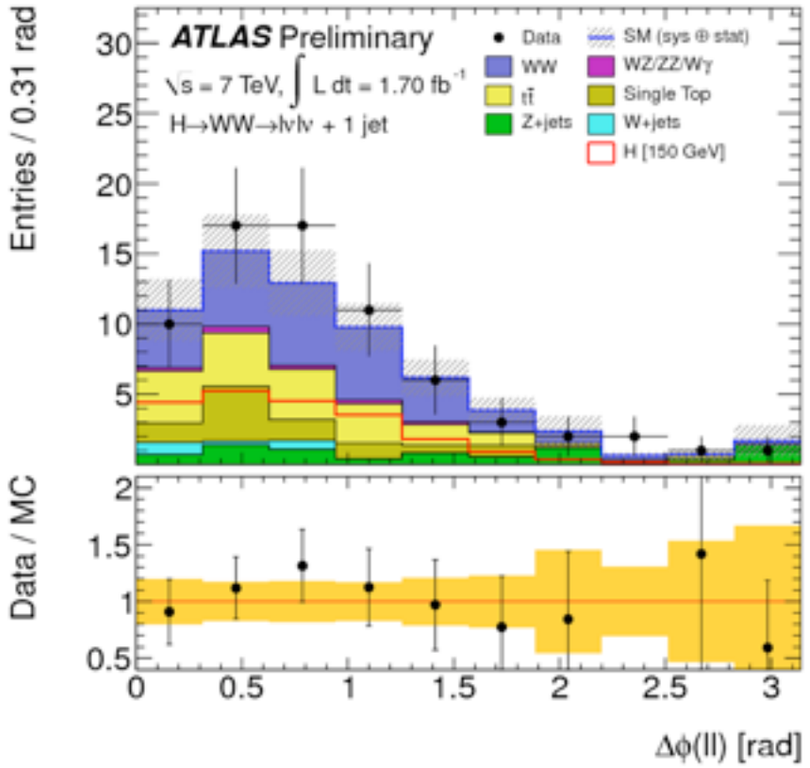
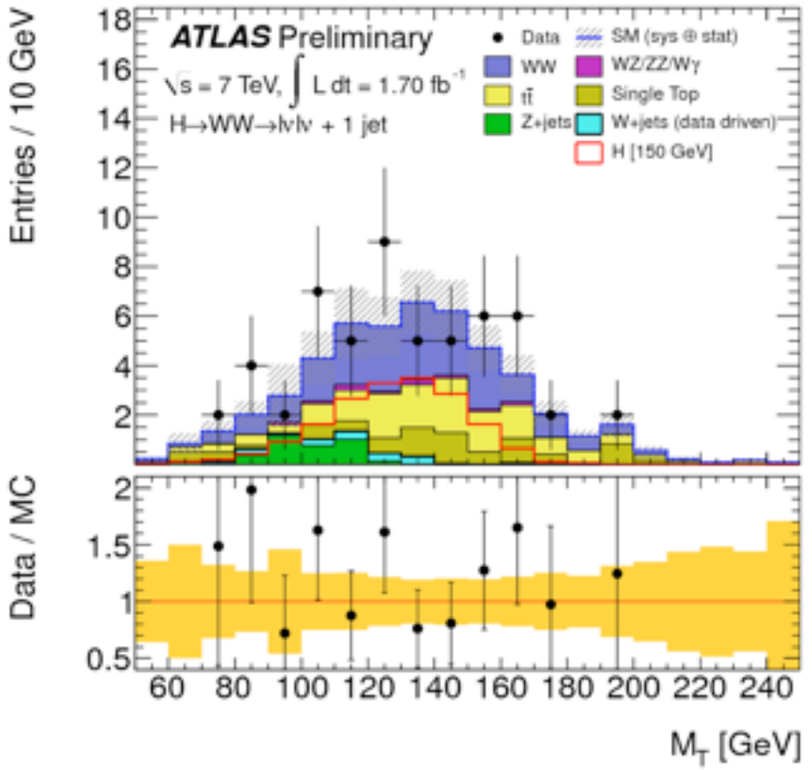
m_H = 150 GeV Selection

	Signal	WW	W + jets	Z/γ^* + jets	$t\bar{t}$	$tW/tb/tqb$	$WZ/ZZ/W\gamma$	Total Bkg.	Observed
1 jet	41 ± 7	158 ± 16	31 ± 19	60 ± 60	390 ± 100	140 ± 20	10.7 ± 1.4	800 ± 120	756
b-jet veto	40 ± 7	154 ± 16	29 ± 18	60 ± 50	140 ± 40	54 ± 9	10.6 ± 1.4	450 ± 70	440
$P_{\mathrm{T}}^{\mathrm{tot}} < 30$ GeV	32 ± 6	127 ± 13	16 ± 9	30 ± 30	90 ± 20	41 ± 7	7.0 ± 0.9	310 ± 50	312
$Z \to \tau\tau$ veto	32 ± 6	124 ± 14	14 ± 7	30 ± 20	84 ± 19	39 ± 7	6.8 ± 1.4	300 ± 30	301
$m_{\ell\ell} < 50$ GeV	22 ± 5	27 ± 5	2.1 ± 1.0	8 ± 6	17 ± 6	9 ± 2	1.5 ± 0.4	64 ± 10	69
$\Delta\phi_{\ell\ell} < 1.3$	19 ± 4	21 ± 4	1.8 ± 0.9	4 ± 5	14 ± 5	8 ± 2	1.2 ± 0.3	50 ± 9	54
$0.75\, m_H < m_{\mathrm{T}} < m_H$	12 ± 3	10 ± 2	0.8 ± 0.4	1.1 ± 1.8	6.9 ± 1.9	3.4 ± 1.4	0.6 ± 0.3	23 ± 4	23
ee	1.7 ± 0.4	1.4 ± 0.4	0.12 ± 0.06	0.07 ± 0.12	0.6 ± 0.3	0.5 ± 0.3	0.10 ± 0.09	2.8 ± 0.7	5
$e\mu$	6.3 ± 1.5	5.7 ± 1.3	0.5 ± 0.3	0.6 ± 1.0	3.7 ± 1.3	2.0 ± 1.0	0.39 ± 0.20	13 ± 3	11
$\mu\mu$	3.9 ± 0.9	3.3 ± 0.7	0.1 ± 0.2	0.5 ± 0.5	2.6 ± 1.5	1.0 ± 0.9	0.08 ± 0.06	8 ± 2	7

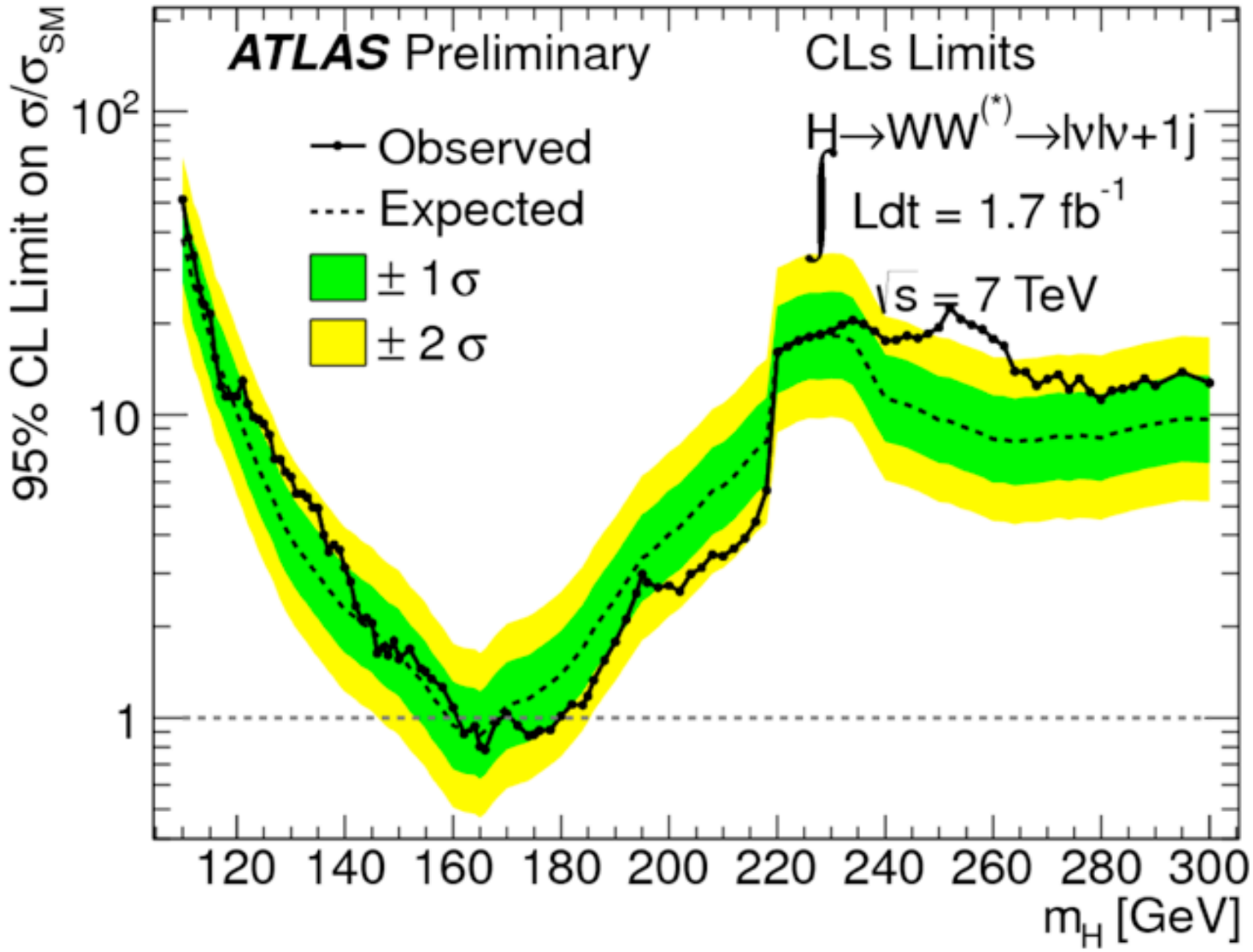






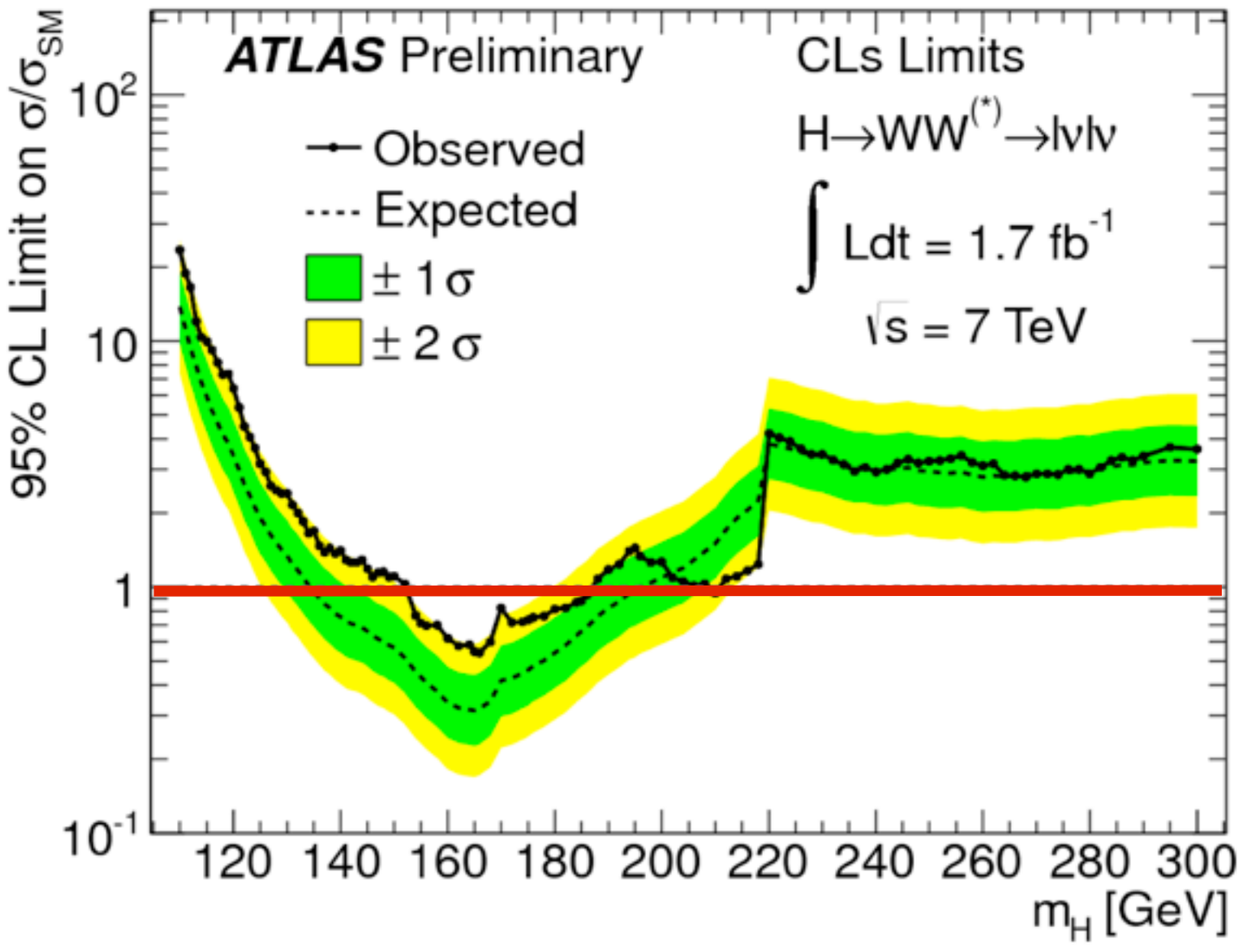
H→WW→lνlν + 1j Limits

Lower sensitivity compared to 0j but very close to the SM cross-section around m_H = 160 GeV



H→WW→lνlν Exclusion Limit

- A SM Higgs boson with 154 < m_H < 186 GeV is excluded at 95% CL by combining 0j and 1j
  - Expected exclusion range is 135 < m_H < 196 GeV
  - Observed limit is within 2σ of the expected limit over the full range



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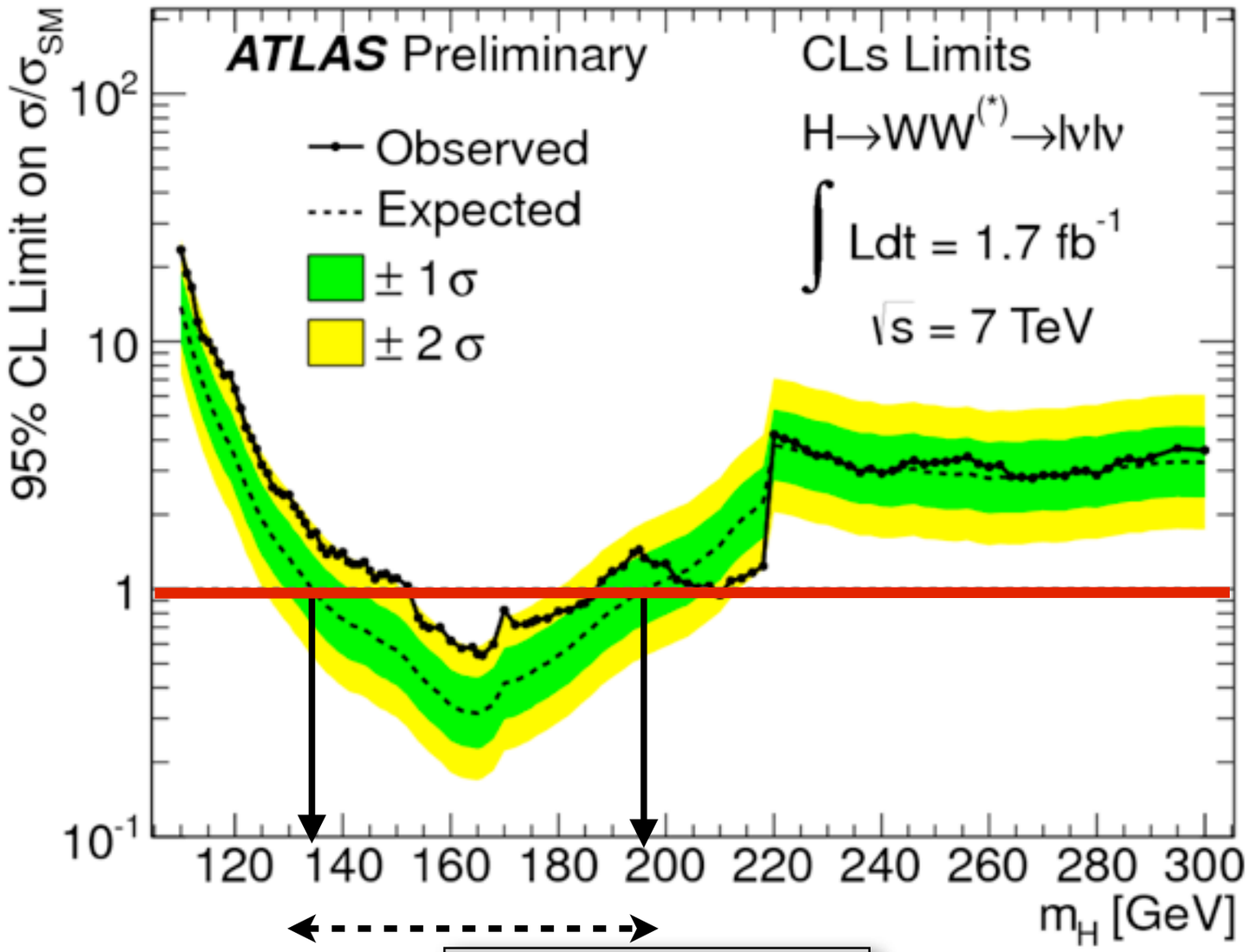

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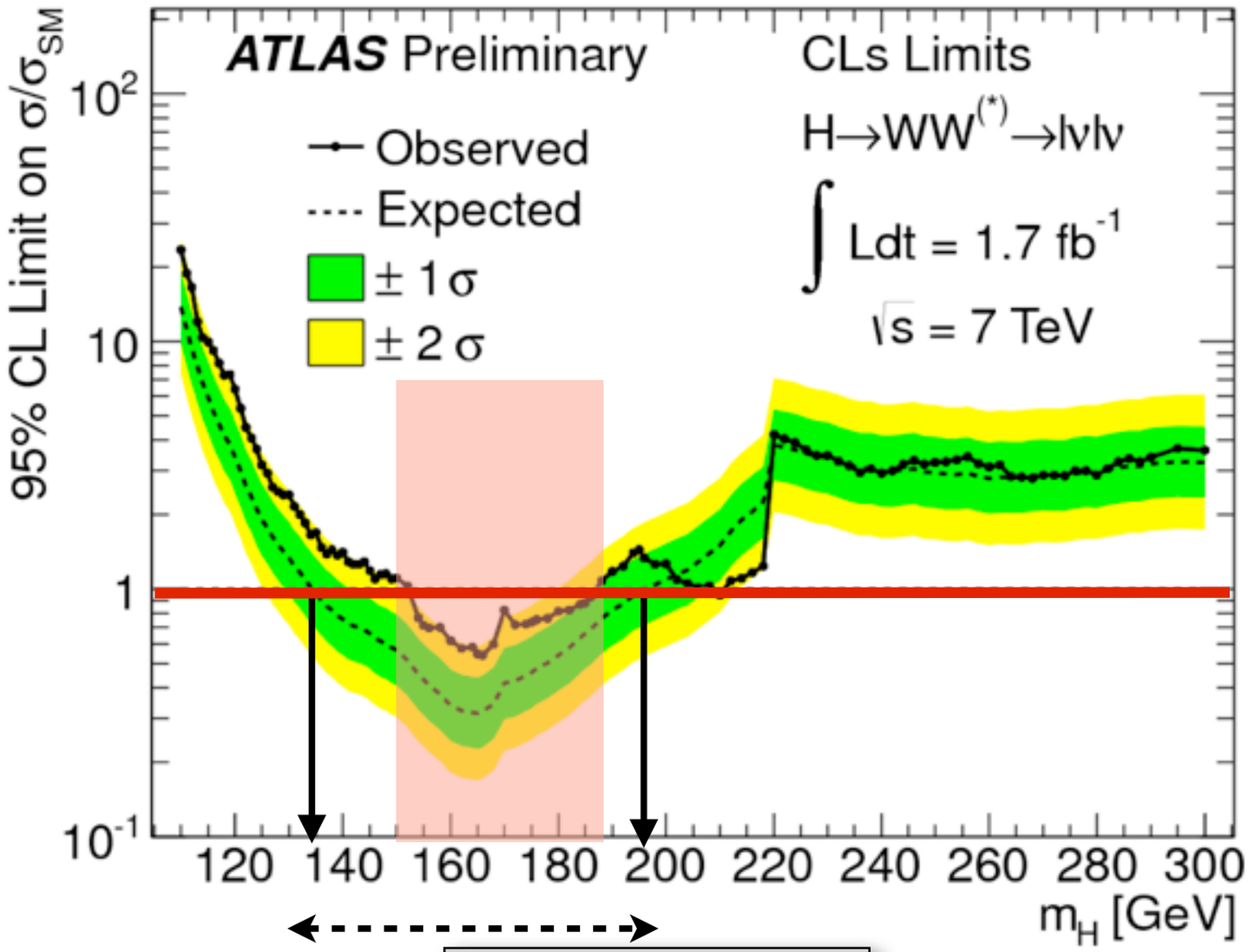

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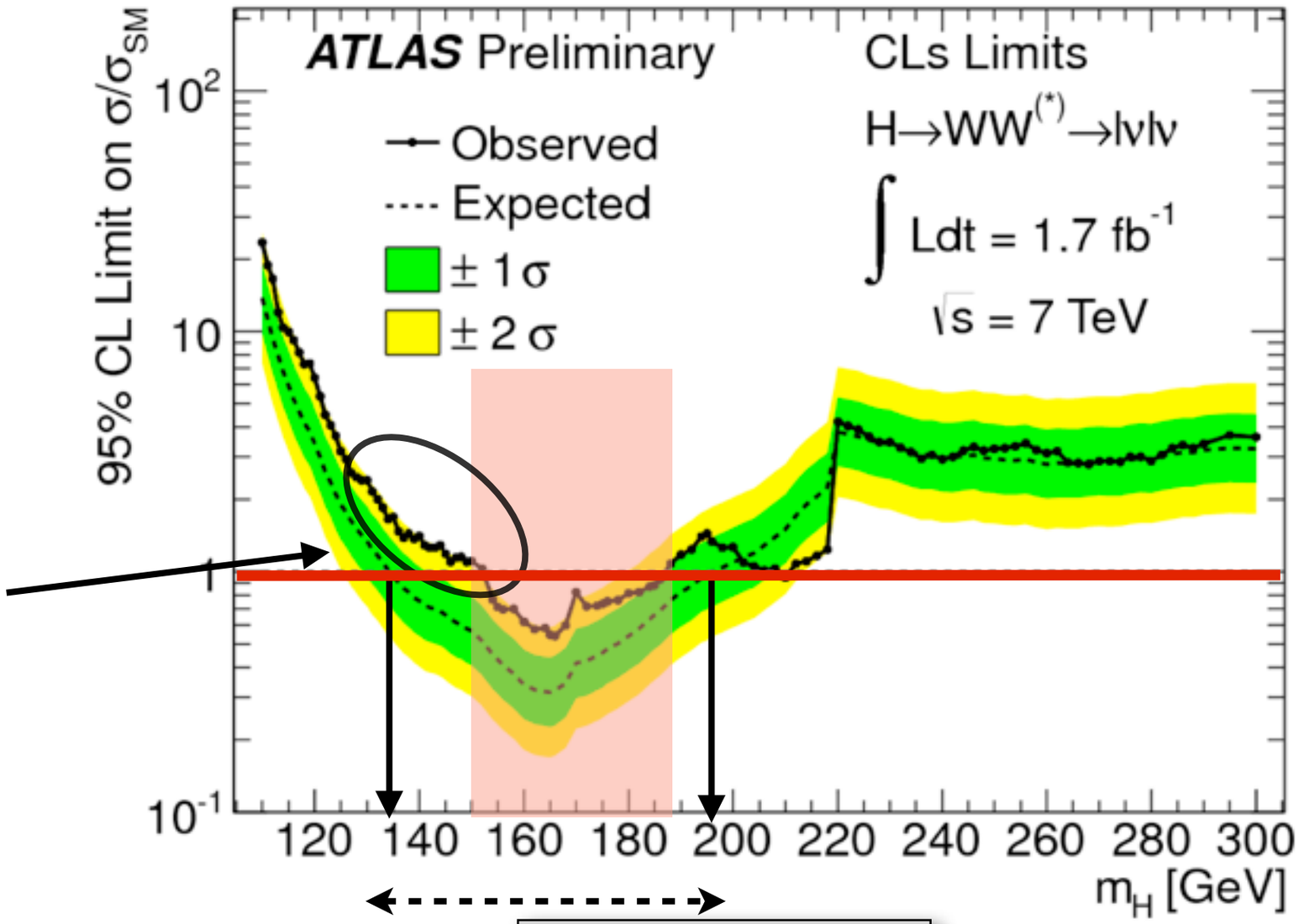
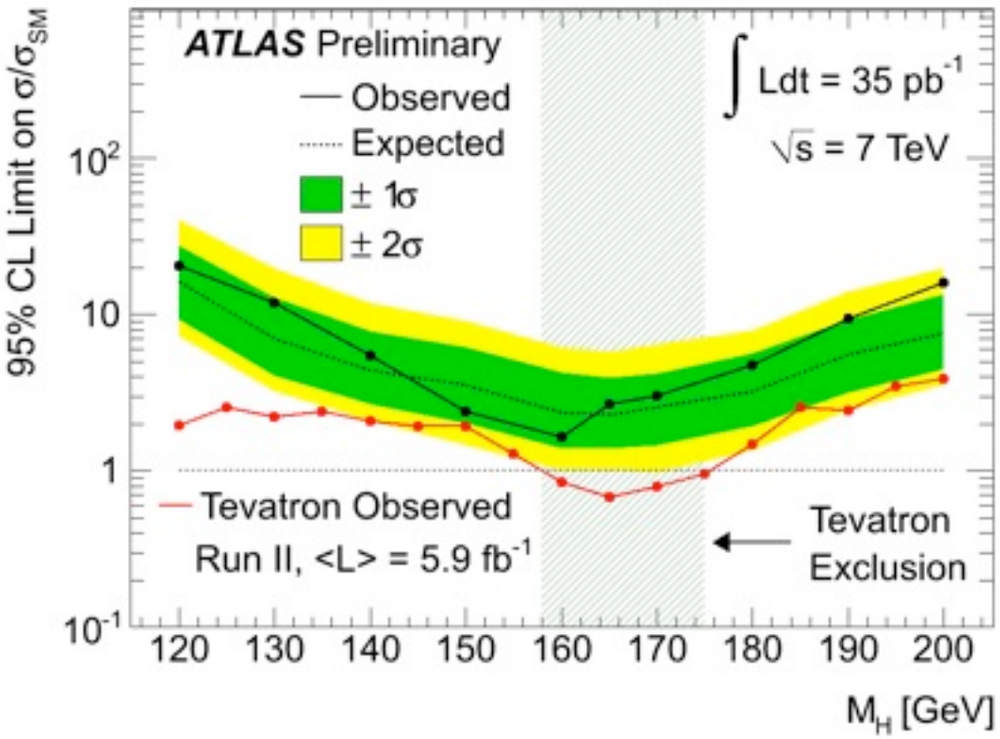


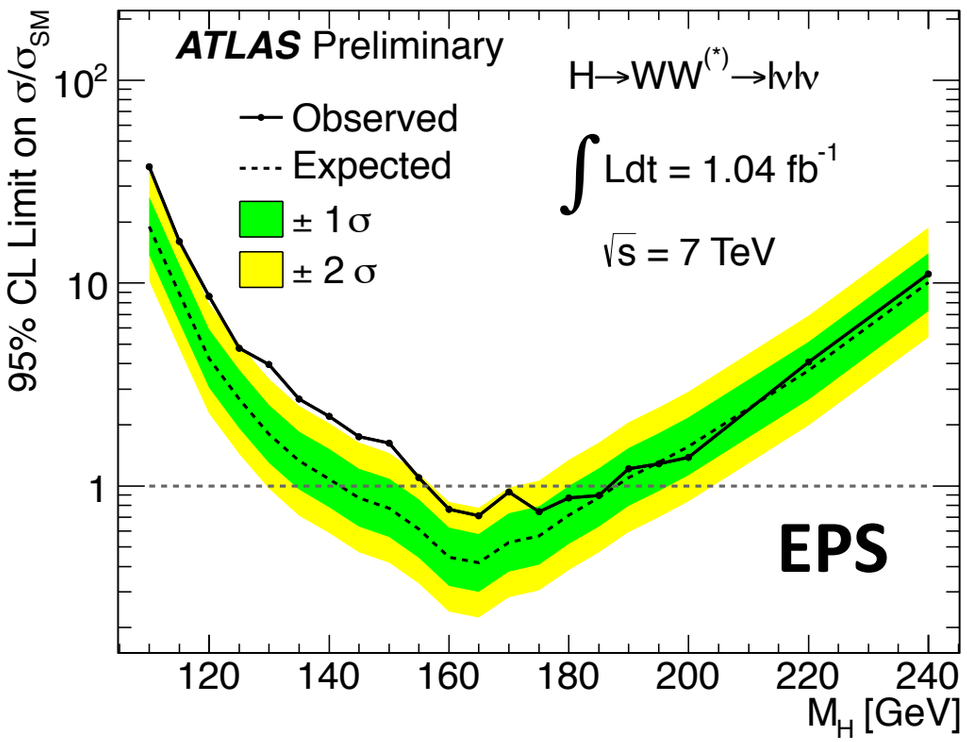
excess of events

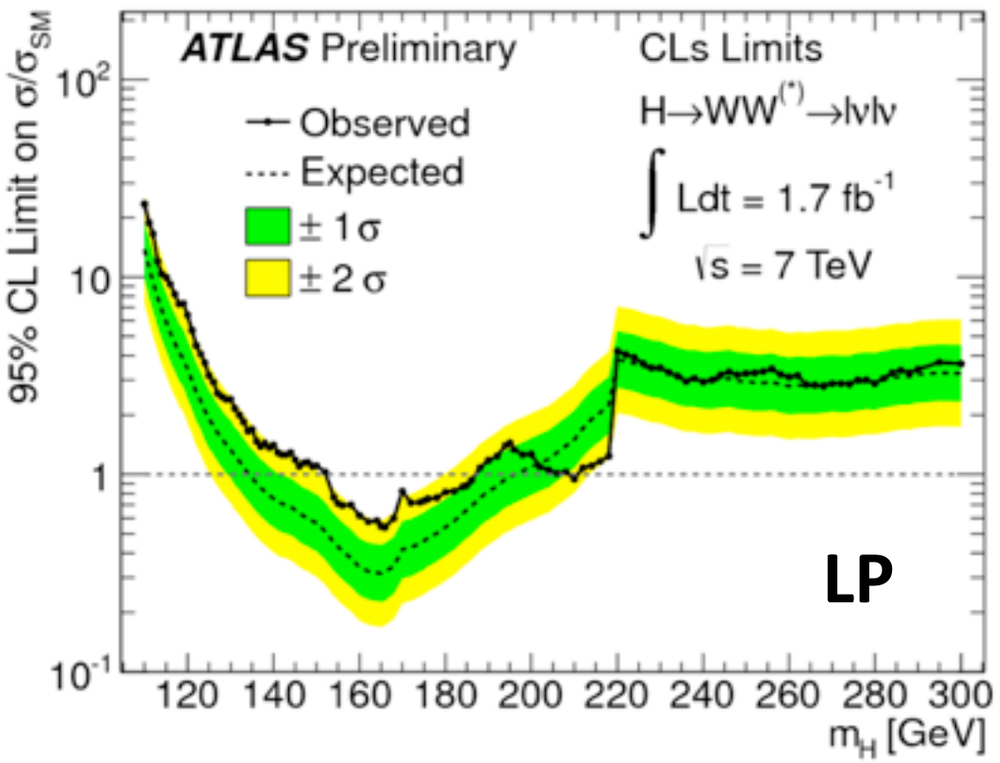
135 < m_H < 196 GeV

154 < m_H < 186 GeV

H→WW→lνlν at ATLAS







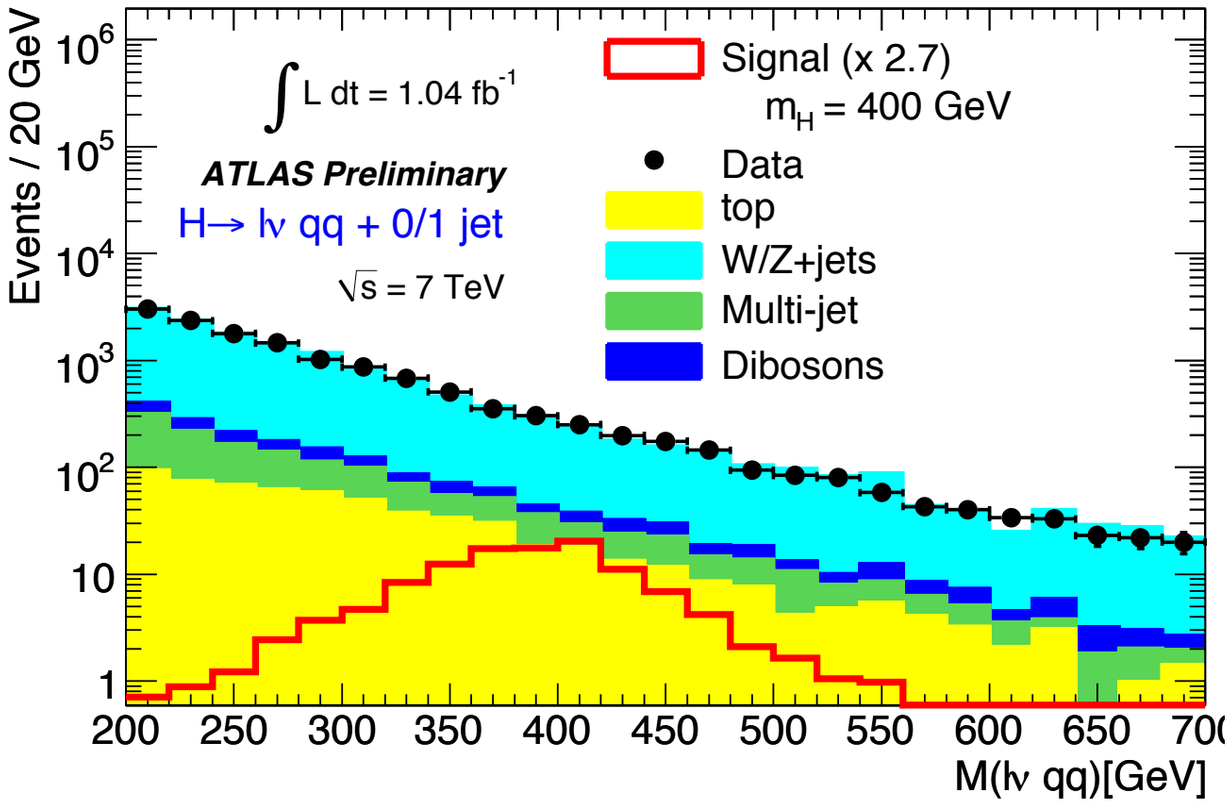
Publication on 2/fb in preparation

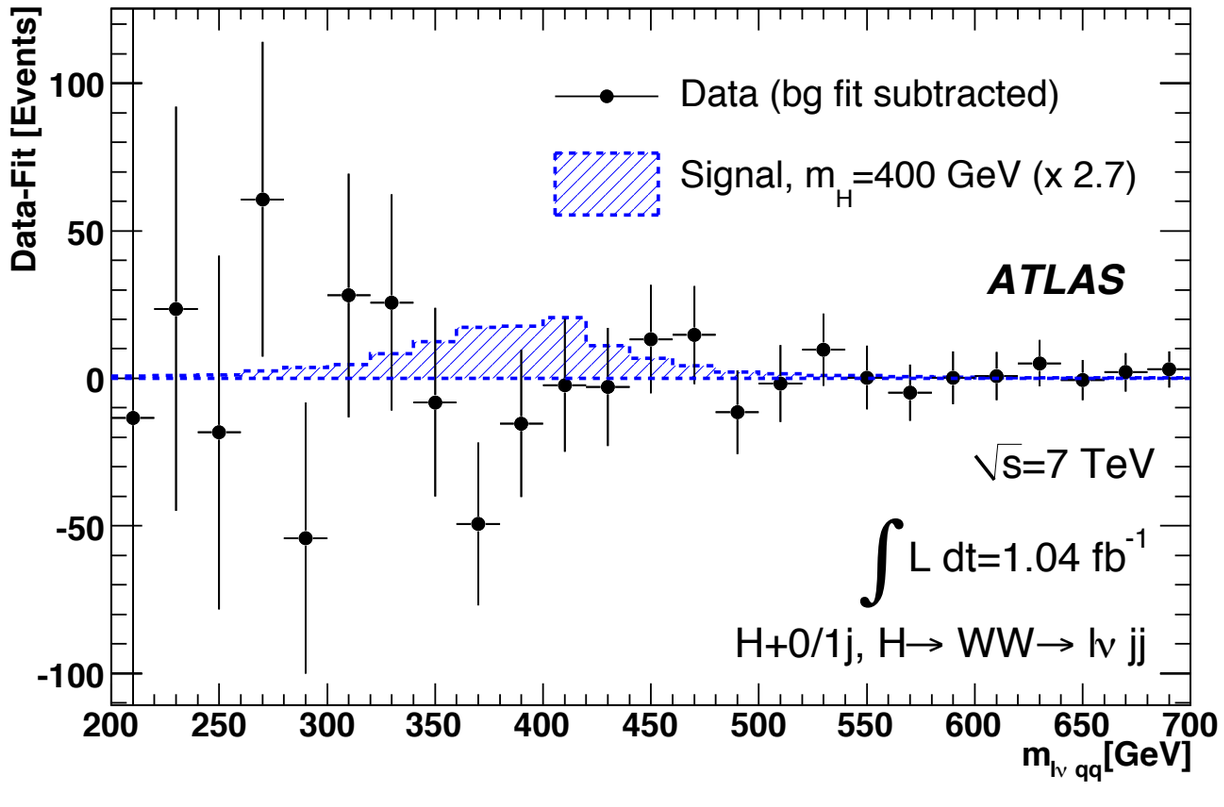
The H→WW→lνqq Analysis

- At larger Higgs mass, it becomes possible to separate the H→WW→lνqq decay from the large backgrounds
- Analysis is performed for 240 GeV < m_H < 600 GeV
  - Best sensitivity for m_H around 400 GeV
- Candidate events with one lepton, large missing E_T and jets
  - one lepton (e, μ) with p_T > 30 GeV
  - missing E_T > 30 GeV
  - Two jets with 71 < M_{jj} < 91 GeV (either 2 or 3 jets)
  - Veto events if any jet is b-tagged
- Reconstruct Higgs mass (Mlνqq) by imposing $M_{l\nu}$=M_W and M_{qq}=M_W
- Strategy is to search for a bump in the $M_{l\nu qq}$ distribution above the strongly falling background

Mass Distribution

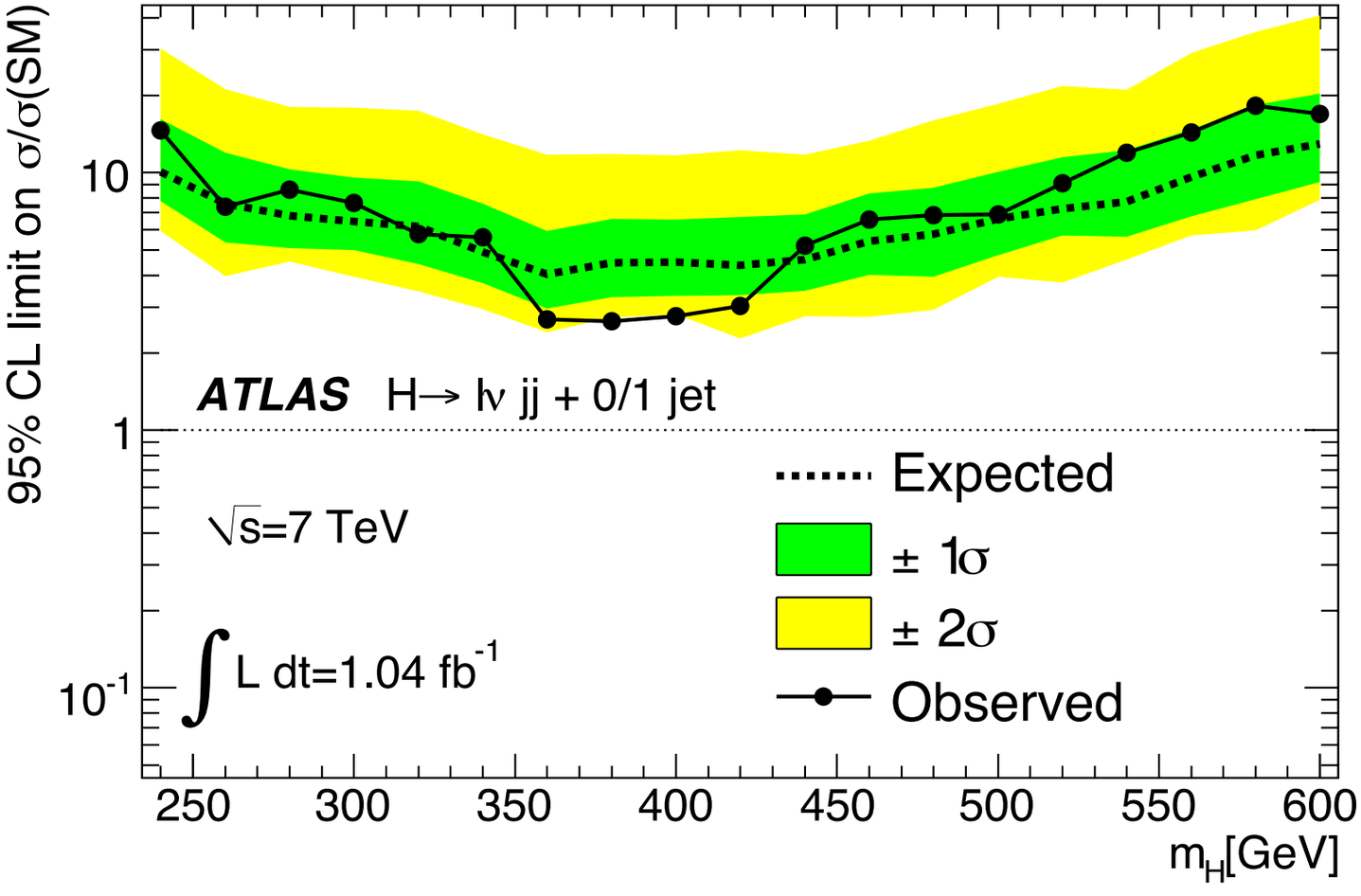
	H($e\nu jj$) + 0j	H($\mu\nu jj$) + 0j	H($e\nu jj$) + 1j	H($\mu\nu jj$) + 1j	H + 0j or 1j
W/Z+jets	10780 ± 290	13380 ± 870	6510 ± 250	7410 ± 670	38080 ± 1160
Multi-jet	890 ± 24	256 ± 17	669 ± 25	212 ± 19	2027 ± 43
Top	170 ± 34	164 ± 33	489 ± 98	500 ± 100	1320 ± 270
Dibosons	397 ± 79	414 ± 83	161 ± 32	204 ± 41	1180 ± 240
Expected Background	12240 ± 300	14210 ± 870	7830 ± 270	8330 ± 680	42600 ± 1200
Data	11988	13906	7543	8250	41687
Expected Signal ($m_H = 400$ GeV)	14 ± 3.6	12 ± 3.1	18 ± 4.7	14 ± 3.6	58 ± 15





Exclusion Limit

- Signal extracted using a maximum likelihood fit to the background modeled by the sum of two exponentials
- For $350 < m_H < 420$ GeV, the 95% CL is ~2.7 x SM cross-section
- Expected limit in this range is ~4 x SM cross-section



arXiv:1109.3615v1, Accepted to PRL

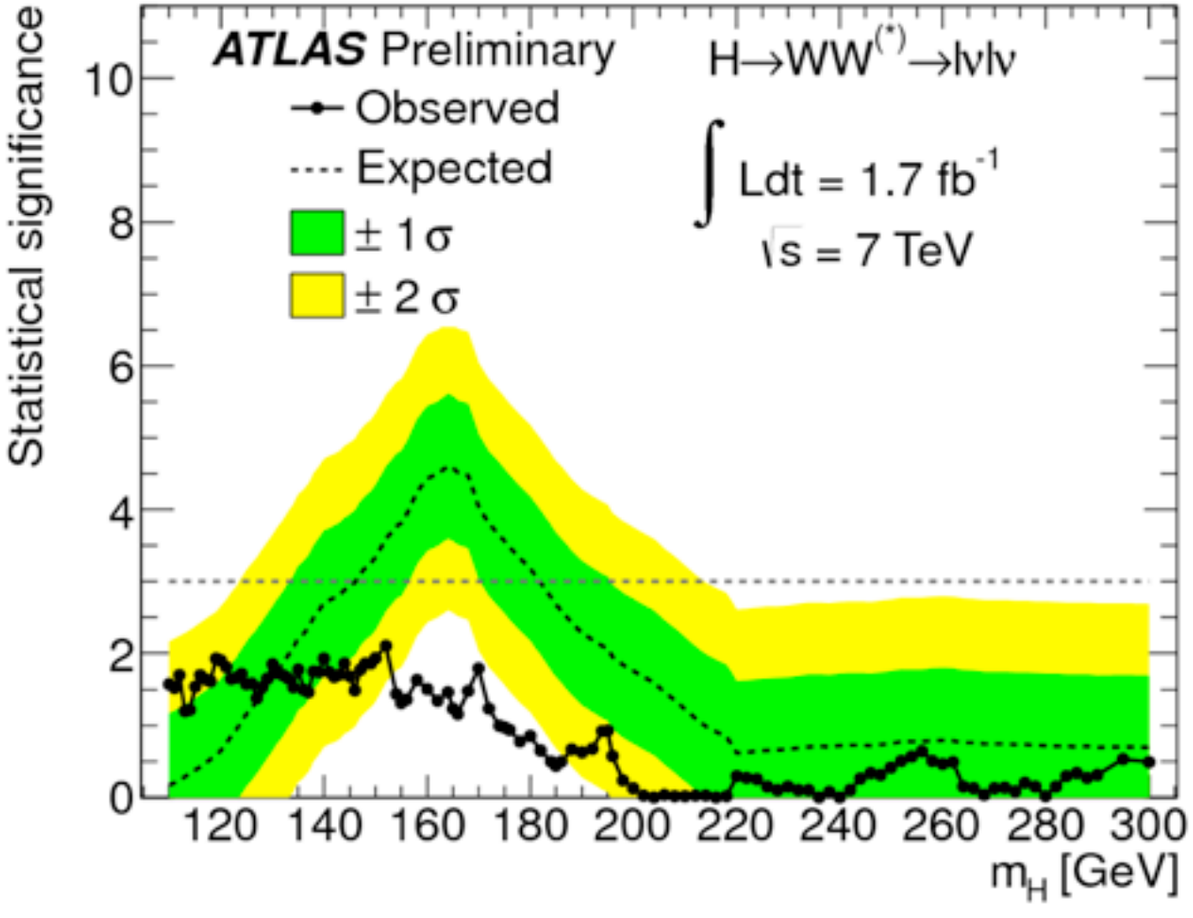
Conclusions

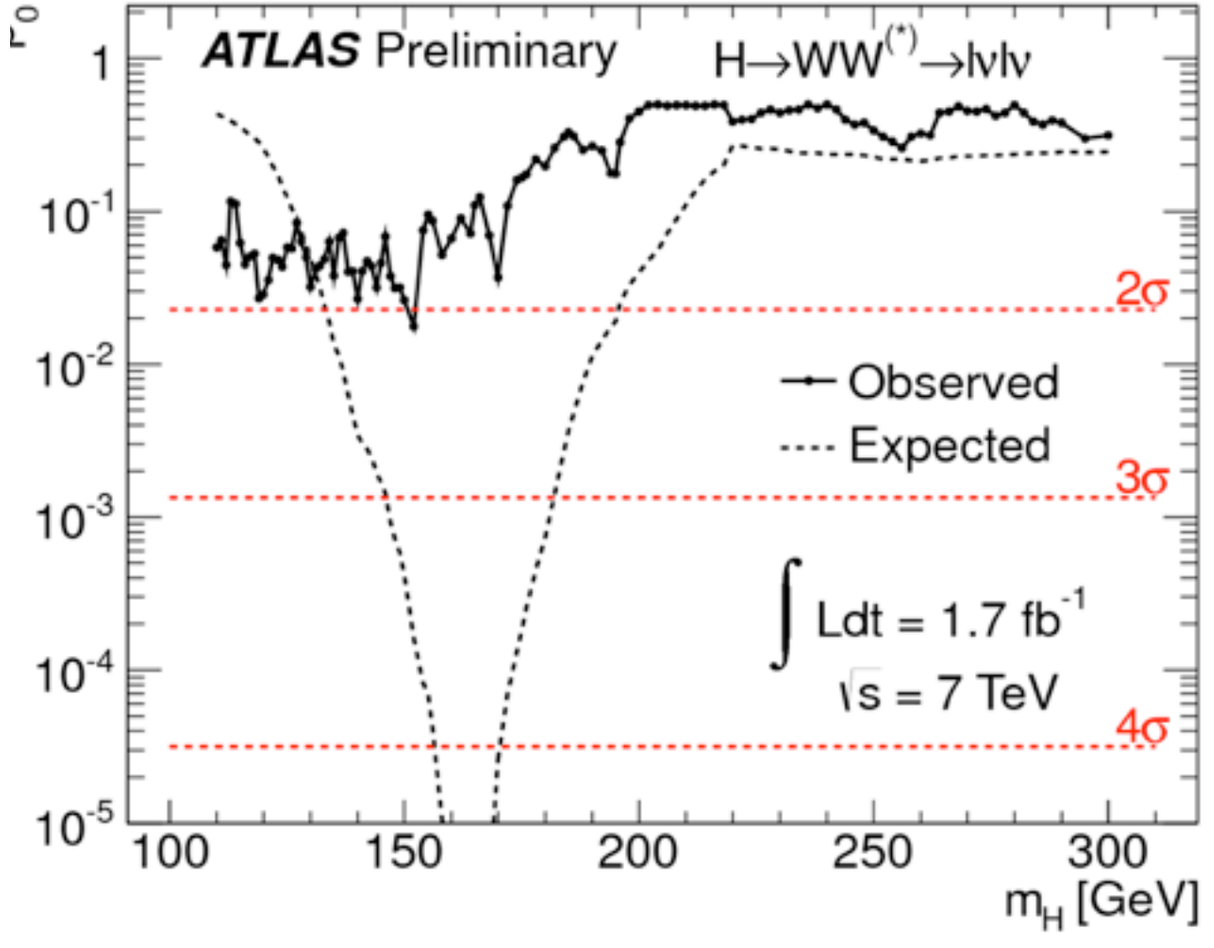
- Presented latest results from ATLAS in the H→WW→lνlν and H→WW→lνqq channels
  - No evidence for the Higgs boson
  - H→WW→lνlν analysis excludes the SM Higgs for $154 < m_H < 186$ GeV at 95% CL with 1.7/fb
  - H→WW→lνqq channel obtains a limit of ~2.7σ SM with 1/fb
- A small deviation of ~2σ between the expected and observed limits is observed in the range $110 < m_H < 150$ GeV in the H→WW→lνlν analysis
  - Neighboring mass points are highly correlated due to the mass resolution

Bonus

Significance and p-values

- Compare expected significance as a function of Higgs boson mass to measured significance
- ~2σ excess for mH < 150 GeV (smaller than that observed with 1/fb)
- p-value is consistent with background only hypothesis within 2σ





Data Driven Background Estimation

Backgrounds either partially or fully determined from data

$N_{S.R.} = \alpha \times N_{C.R.}$

Signal Region
Higgs(VBF+ggF)
WW
tt + single t
W jets

$$\alpha_{WW} = \frac{N_{WW}^{sig}}{N_{WW}^{ctrl(WW)}}$$

$$\alpha_{tt} = \frac{N_{top}^{sig}}{N_{top}^{ctrl(top)}}$$

$$\alpha_{Wj} = \frac{N_{dijet}^{SR}}{N_{dijet}^{CR}}$$

WW control
WW
tt + single t
W jets

top control
tt + single t

W control
W jets

remove $\Delta\varphi$ and m_T cuts, invert m_{ll} cuts

$$\beta_{tt} = \frac{N_{top}^{ctrl(WW)}}{N_{top}^{ctrl(top)}}$$

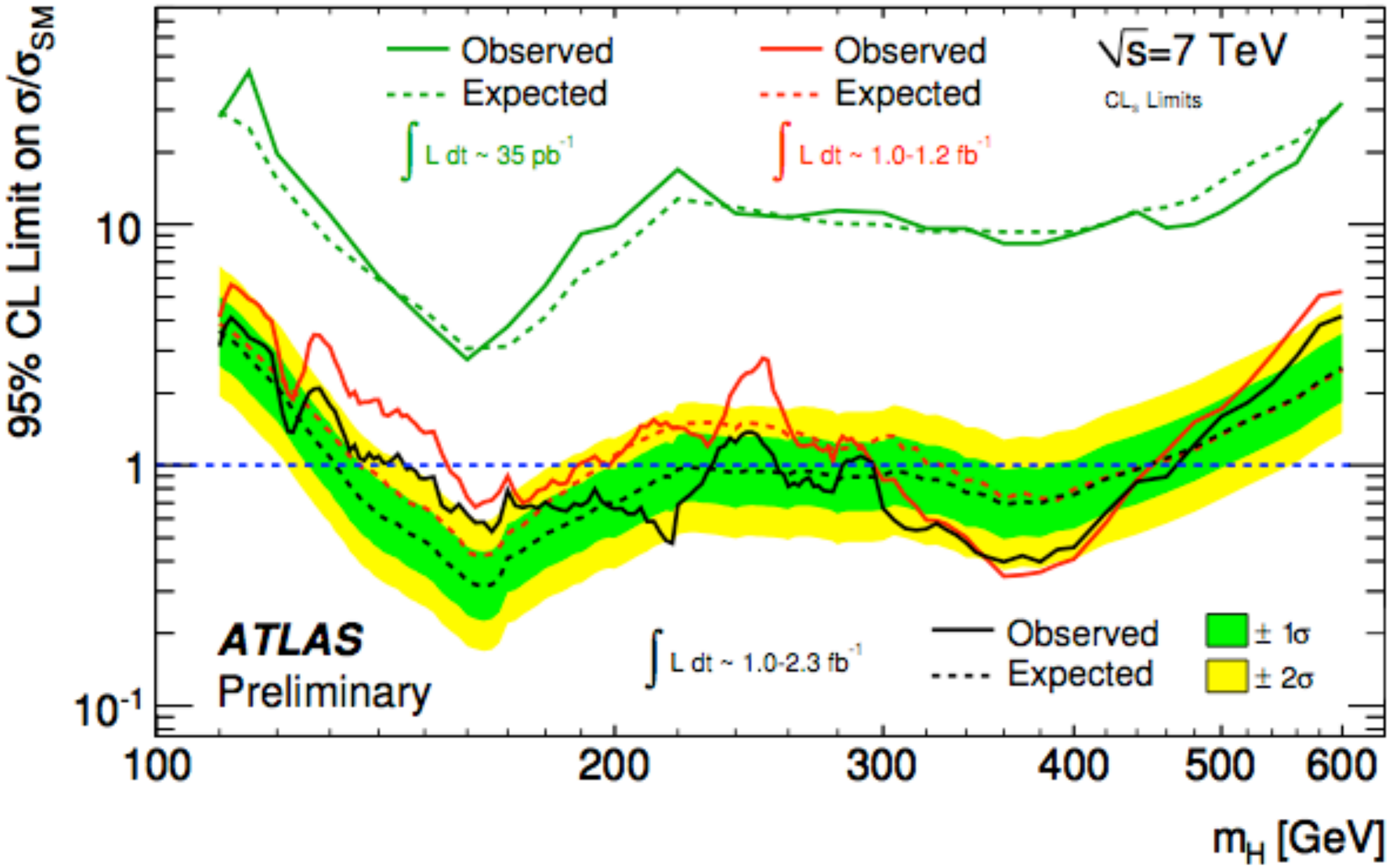
$$\beta_{Wj} = \frac{N_{Wj}^{ctrl(WW)}}{N_{Wj}^{ctrl(Wj)}}$$

1j: remove topological cuts, invert b-jet veto

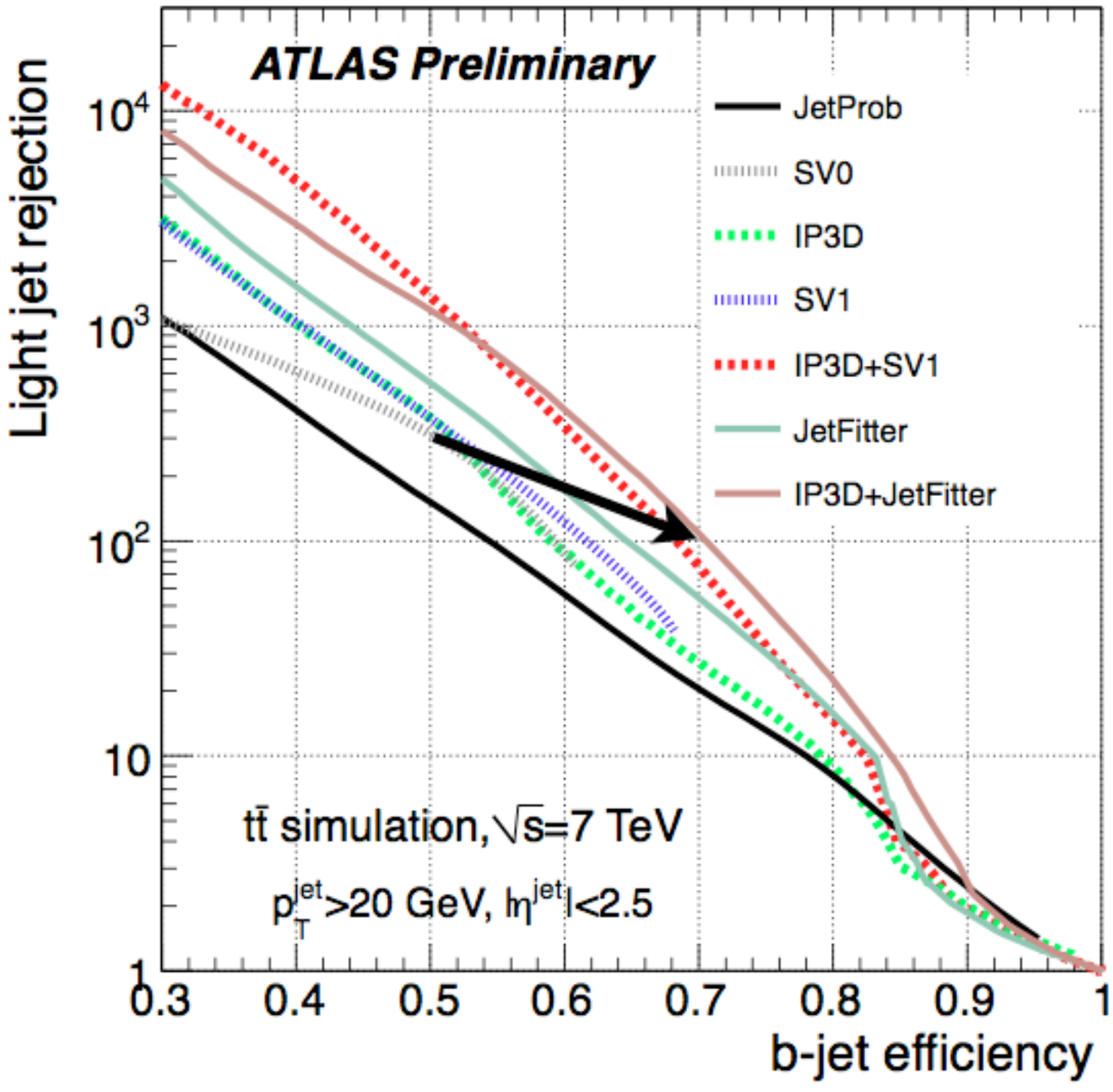
require 2nd lepton to fail tight selection, but pass loose selection

0j: estimate top background from b-jet survival probability

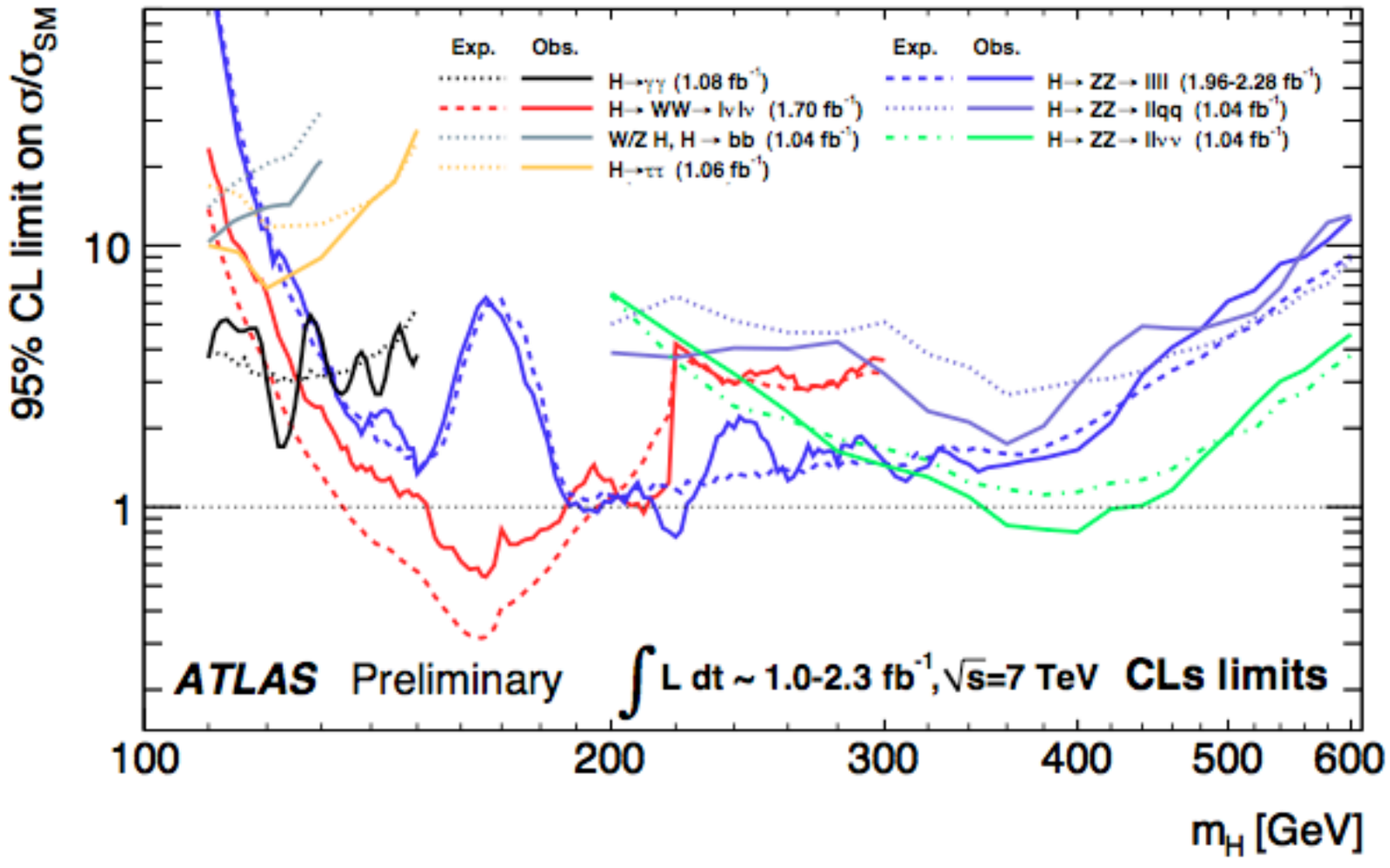
ATLAS Higgs Combination



B-tagging


ATLAS Preliminary
JetProb
SV0
IP3D
SV1
IP3D+SV1
JetFitter
IP3D+JetFitter
tt̄ simulation, √s=7 TeV
p_T^jet>20 GeV, |η^jet|<2.5
Light jet rejection
b-jet efficiency
10^4
10^3
10^2
10
1
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

ATLAS Combination



Systematic Uncertainties

Source of Uncertainty	Treatment in the analysis
Jet Energy Resolution (JER)	~ 14%, see Ref. [69]
Jet Energy Scale (JES)	Takes into account close-by jets effect, jet flavor composition uncertainty and event pile-up uncertainty in addition to global JES uncertainty Global JES < 10% for p_T > 15 GeV and $\|\eta\|$ < 4.5, see Ref. [70] Pile-up uncertainty 2-5% for $\|\eta\|$ < 2.1 and 3-7% for 2.1 < $\|\eta\|$ < 4.5 These are summed in quadrature before application.
Electron Selection Efficiency	Separate systematics for electron identification, reconstruction and isolation, added in quadrature Total uncertainty of 2-5% depending on η and E_T
Electron Energy Scale	Uncertainty smaller than 1%, depending on η and E_T
Electron Energy Resolution	Energy varied within its uncertainty, 0.6% of the energy at most
Muon Selection Efficiency	0.3-1% as a function of η and p_T
Muon Momentum Scale	η dependent scale offset in p_T, up to ~ 0.13%
Muon Momentum Resolution	p_T and η dependent resolution smearing functions, ≤ 5%
b-tagging Efficiency	p_T dependent scale factor uncertainties, 5.6-15%, see Ref. [71]
b-tagging Mis-tag Rate	up to 21% as a function of p_T, see Ref. [71]
Missing Transverse Energy	13.2% uncertainty on topological cluster energy Electron and muon p_T changes from smearing propagated to MET Effect of out-of-time pileup: MET smeared by 5 GeV in 1/3 of MC events
Luminosity	3.7% [25]

	α_{WW}^{0j}	α_{WW}^{1j}	α_{top}^{1j}	β_{top}^{1j}
Q^2 Scale	2.5%	4%	9%	–
MC Modeling	3.5%	3.5%	4%	–
PDF	3.8%	3.5%	3%	–
Jet E Scale + Resolution	$^{+0.5}_{-0.6}$%	$^{+2.3}_{-1}$%	$^{-35}_{+32}$%	$^{-36}_{+32}$%
b-tagging Efficiency	–	–	$^{-23}_{+23}$%	$^{-19}_{+20}$%
MC Statistics	4.3%	12.9%	6%	–

Process	jet bin	Scale	PDF	MC	Total
WW	0 jet	4%	3%	7%	9%
	1 jet	5%	3%	10%	12%
$t\bar{t}$	0 jet	9%	3%	8%	12%
	1 jet	4%	3%	8%	9%
$gg \to H$	0 jet	3%	3%	3%	5%
	1 jet	3%	3%	11%	12%

$Z \rightarrow \tau\tau$ Rejection

- Reconstruction $m_{\tau\tau}$ by assuming
- leptons arise from $Z \rightarrow \tau\tau$ decays
- neutrinos are collinear with the leptons
- Reject the event when
  - the energy fractions of the visible decay products are positive
    - i.e. $x_{\tau 1} > 0$ and $x_{\tau 2} > 0$
  - and the invariant mass is consistent with the Z
    - i.e. $|m_{\tau\tau} - M_Z| < 25$ GeV
- Only applied in H + 1j, because in H+0j the leptons are more often back-to-back